Chapter 3 Component Design, R&D Strategy & Results, Construction Status

3. 1 Linac

3. 1. 1 Ion Source

The required parameters for the ion source are shown in Table 3.1.1.1. No ion source in the world satisfies all of the requirements simultaneously. Especially, the lifetime is the most difficult issue to be solved.

Table 3.1.1.1 Required parameters for the joint project ion source.

Ion	Emittance(4rms, normalized)	Peak current	Duty factor	Lifetime
H^-	0.67 π·mm·mrad	>55 mA	>3.0%(600 μs*50 Hz)	3weeks(504 hours)

*4-times rms of 1 π·mm·mrad (water bag 100%) is 0.67 π·mm·mrad .

The volume production type ion source seems most promising to accomplish the requirements. The other two high intensity proton projects (SNS and ESS) also adopted the same type ion source. However, the SNS ion source [1] uses RF-driven discharge and the ESS ion source [2] uses filament discharge to produce plasma. Before two past projects were integrated into the joint project, the research and development (R&D) of two ion sources using these two different plasma production systems have started for each past project. The recent experimental results of each ion source are summarized in Table 3.1.1.2. The joint project ion source will be designed by using the results, which have been acquired and will be acquired within a next half year with these ion sources, since each system has own strong points and shortcomings.

Table 3. 1. 1. 2 Recent experimental results of the joint project ion sources.

Ion Source Type	Volume filament discharge	Volume RF-driven
Institute	JAERI	KEK
Extracted beam energy	70 keV	50 keV
Measured beam current	14 mA (pure volume) 72 mA (Cs seeded)	20 mA (pure volume)
Current measurement method	Faraday cup	Faraday cup
Electron H^- ratio	< 1	~5
Electron suppression	Magnetic deflection	Magnetic deflection

Duty Factor	5.0 %	3.0 %
Lifetime	～120 h (filament) @Arc power : 30 kW Duty factor : 3 %	not measured
Breakdown Frequency	～2 / hour	< 1/hour
Measured emittance, normalized, rms	0.13 (X), 0.15 (Y) π·mm·mrad @60 mA, 70 keV	{0.10(X), 0.11(Y) π·mm·mrad @7 mA, 50 keV filament discharge operation}
Emittance measurement method	Double slit scan	double slit scan
Location of device	0.6 m from plasma electrode	0.5 m from plasma electrode
Extraction aperture		
Number of apertures	1	1
Aperture radius, mm	4.0	3.5
Arc power, kW	56 @H^- current : 72 mA	
RF frequency, MHz		2 (main), 30 (sub)
RF power, kW		30 @H^- current:16 mA
Gas flow, sccm	～18	～15
Material of cathode or antenna	tungsten filament	Ti antenna
Cesium	Used	not used
Other		dual frequency plasma production

a. Filament Discharge Ion Source

A filament discharge H^- ion source has been developed in collaboration with the JAERI nuclear fusion group. A cross-sectional view of the ion source is shown in FIG 3.1.1.1. A cylindrical plasma chamber, whose dimensions are 150 mm in diameter and 200 mm in length, is installed outside of the insulator so as to change the configuration of the cusp and the filter magnets easily. The source plasma is produced by arc discharge using two tungsten filaments. The dimensions of the filament are 260 mm in total length and 1.5 mm in diameter. Some of Nd-Fe-B permanent magnets surrounding the chamber wall generate a multi-cusp magnetic field, while the other ones producing a magnetic filter field. The cesium vapor produced in an oven was introduced into the plasma chamber.

The beam extractor consists of three electrodes referred to as a plasma electrode (PE), an extraction electrode (EXE) and a grounded electrode (GE). H^- ions are extracted trough a single aperture of 8 mm in diameter. The gap lengths between the PE and the EXE, and the EXE and the GE are 2.2 mm and 8.35 mm, respectively. The PE is made of 2-mm thick molybdenum plate. The work function of the PE surface is minimized when the cesium produce mono-atomic layer on the surface. The number of the cesium atomic layers is the function of the temperature of the PE and the density of the cesium vapor. Therefore, the H^- ion production rate is strongly dependent on the PE temperature [3]. The PE was heated up around 400 - 500 °C by the energy of the radiation from the filaments and the pulsed arc discharge. The temperature was monitored by a thermocouple installed on the PE. The EXE is made of a 10-mm thick copper plate with a cooling water channel. In the EXE, Sm-Co permanent magnets are inserted in order to produce a dipole magnetic field in the vertical plane, which deflects the extracted electrons and prevents the electrons from leaking to the acceleration gap. The GE is made of a 2.0 mm thick copper plate with a cooling water channel.

In order to decrease the beam loss due to the electron stripping caused by collisions with the residual hydrogen gas in the beam transport line, two differential vacuum pumping ports are equipped with the ion source. In the beam test, a turbo molecular pump of 1,300 liter/sec is installed at each of the ports. When the differential pumping system was used, the vacuum pressure in the beam line was improved from 1.0×10^{-2} Pa to 1.0×10^{-3} Pa.

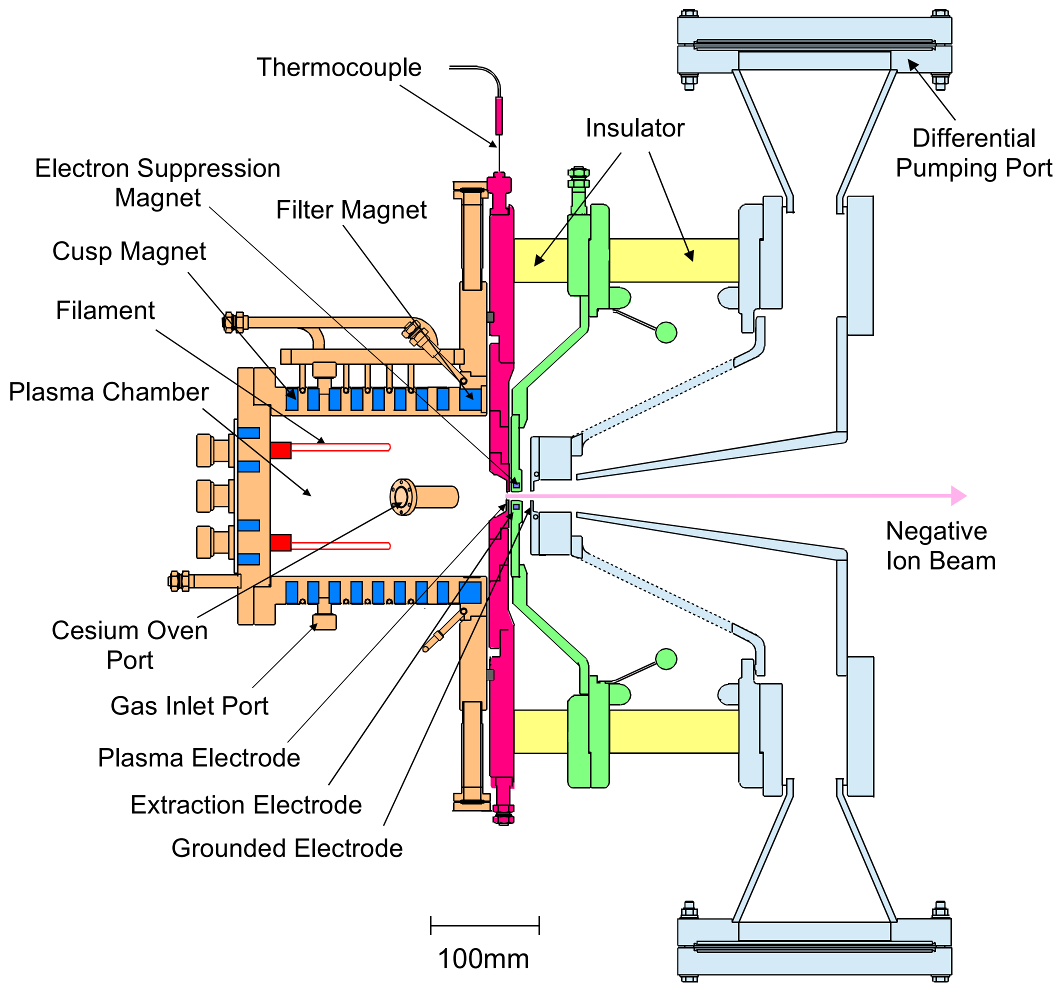

FIG 3.1.1.1 Cross-sectional view of the filament discharge H^- ion source.

FIG 3.1.1.2 shows the H^- ion current and the extraction current as a function of the arc discharge power for the operations with cesium (Cs seeded) and without cesium (pure volume) at a beam energy of 70 keV. The extraction current corresponds to the electron current injected into the extraction electrode. In the pure volume operation, the ion current saturated at high arc power and was limited to about 14 mA. In the cesium-seeded operation, on the other hand, the beam current was enhanced and almost linearly increased with the arc power. A H^- ion current of 72 mA was extracted at an arc power of 56 kW. In addition, the extraction current decreased remarkably in the cesium-seeded operation. An electron to H^- ion current ratio (e/H^-) was less than unity in the cesium-seeded case, while it was 20 in the pure volume case at 50 kW. This is favorable for the high duty operation, because the heat dissipation on the EXE due to the electron impact makes significant damage on the EXE for high duty operation.

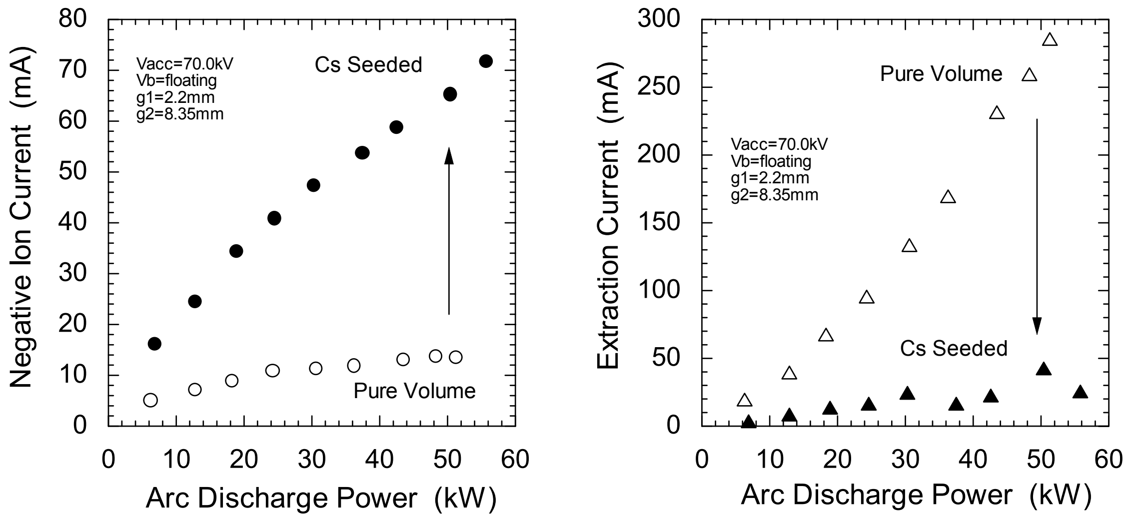

FIG 3.1.1.2 H^- ion current and extraction current as a function of the arc discharge power with and without cesium.

The emittance was measured by using a double slit type scanner installed in the horizontal plane at 0.6 m downstream from the PE. The emittance diagrams in the horizontal phase space (X : left plot) and vertical phase space (Y : right plot), measured at the beam energy of 70 keV and a peak current of 60 mA, are shown in FIG 3.1.1.3. The horizontal and vertical normalized rms emittances are calculated as 0.13 (X) and 0.15 (Y) π·mm·mrad, respectively. The ellipses drawing together with the diagrams show the normalized emittance of 1.5 π·mm·mrad. The RFQ following the ion source is designed to accelerate around 90% of the beam with a emittance of 1.5 π·mm·mrad. The possible causes of the larger emittance of the vertical phase space than that of the horizontal phase space are as follows; one is the influence of the dipole magnetic field in the EXE, and the other is the difference of the space charge effect on the beam, since the vacuum pressure in the beam diagnostic chamber was higher in the vertical measurement than that of the horizontal one due to the different gas flow rate.

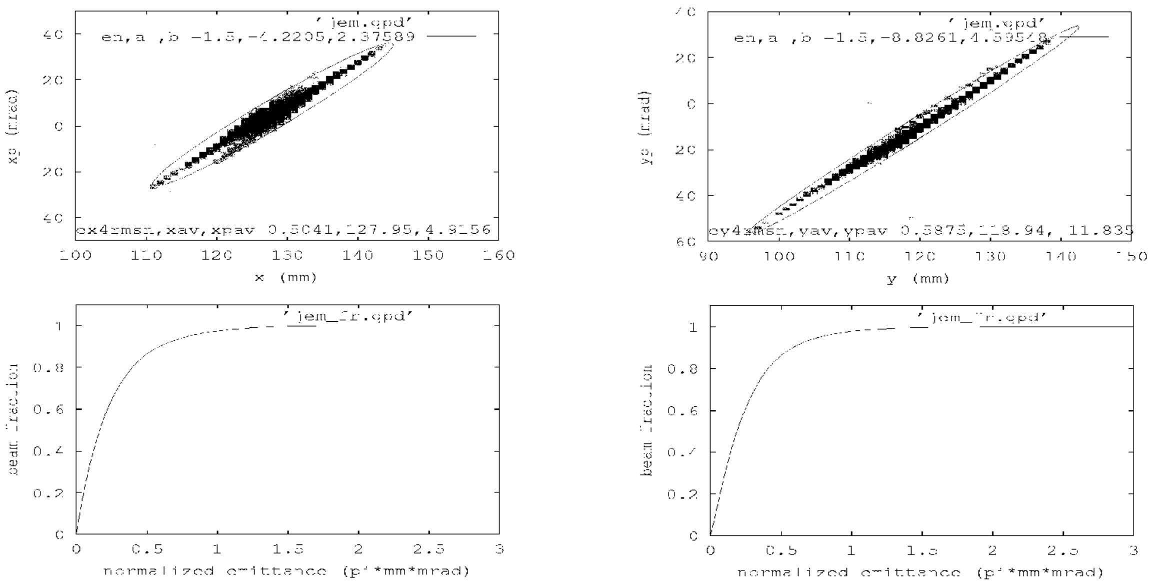

FIG 3.1.1.3 Emittance diagrams at 70 keV and 60 mA.

The measured waveforms of a H^{-} ion current of 72 mA and an arc current of about 380A are shown in FIG 3.1.1.4. The gas flow rate was 18 SCCM. The duty factor was 5 % (pulse width of 1.0 ms and repetition rate of 50 Hz). The rise and fall time of the ion current were about 0.25 ms and 0.15 ms, respectively. The ion source is operated with the optimum gas flow rate, which gives a good flatness of the beam current. In lower (higher) gas flow rate operation than that of the optimum one, the beam current decreased (increased) monotonously with the time [5]. The beam flatness is an important issue, since the variation of the beam intensity during the pulse induces the beam loss in the accelerator due to .

The achieved beam current and emittance satisfy the ion source requirements for the joint project by using the cesium. But the chemically active cesium vapor may cause a sparking problem in the RFQ. Further study is necessary in order to evaluate the affects of cesium vapor introduced in an RFQ as well as the improvement of the ion source performance.

The lifetime of the filaments was measured to be about 120 hours at an arc discharge power and a duty factor of 30 kW and 3.0 %, respectively. The lifetime is expected to lengthen by increasing the number of filaments and the diameter of each filament. The lifetime with modified filaments will be measured in near future.

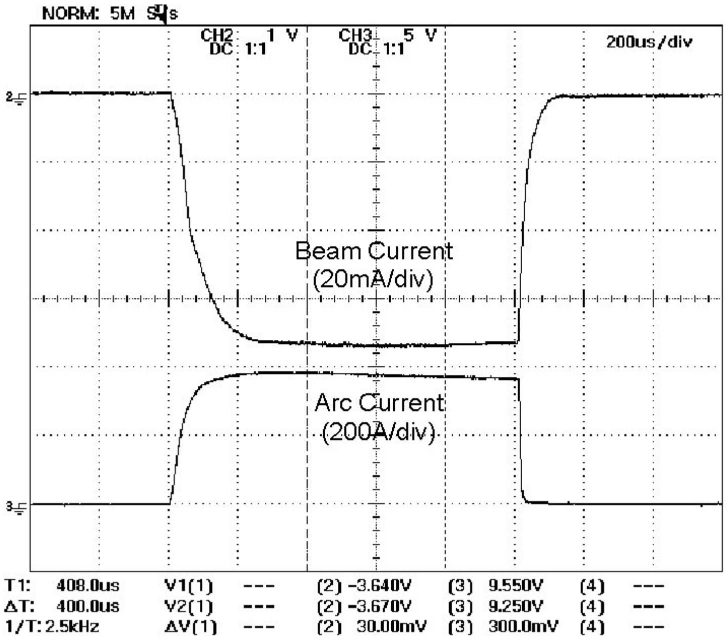

FIG 3.1.1.4 Typical waveforms of H^- ion beam current and arc current operating with 1.0msec pulse duration.

b. RF-driven Ion Source

The R&D of the RF-driven ion source started based upon the following strategy.

(1) An ion source suitable for the joint project LEBT is developed based upon the SNS ion source collaborating with LBNL (Ka-Ngo Leung), since only the SNS ion source succeeded in operating with a high peak arc-power more than 30 kW and a duty factor higher than the joint project requirement without any filament, which is a part with a finite lifetime.

(2) The marginal capacity of the ion source without cesium is examined at first, since there is a possibility that a significant beam loss occurred by sparking in high-voltage gapes (extraction and acceleration gaps of ion source or inter-vane gaps of RFQ and so on) due to the cesium, especially for a long term operation more than ten years.

A schematic drawing of the RF-driven ion source is shown in FIG 3.1.1.5. Although the ejection angle error of the beam mainly produced by the field of the filter and electron suppression permanent magnets is corrected by mechanically tilting the arc-chamber in the SNS ion source, it is corrected by using an ejection angle correction electromagnet located in the vacuum chamber on the end flange in the RF-driven ion source. By using the electromagnet, the correction according to the different operating parameters (the extraction and acceleration voltage, the temperature of the permanent magnets and so on) is possible within an operation. The installation of the correction electromagnet is practically difficult in the SNS-LEBT design philosophy, in which the space charge neutralization is eliminated by existence of electric field on the beam axis.

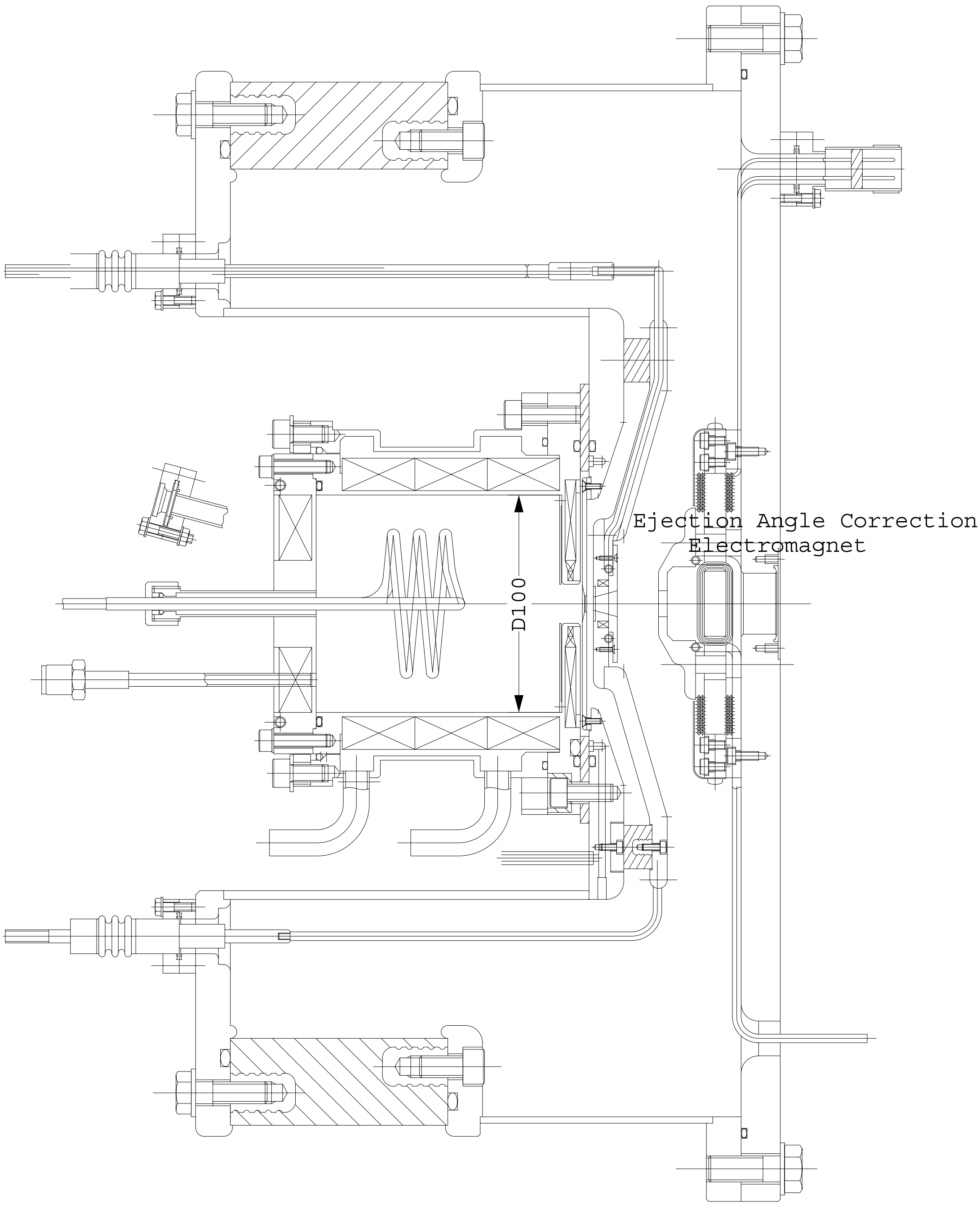

FIG 3.1.1.5 Schematic drawing of RF-driven ion source.

The ion source could not be operated with 2MHz-RF plasma about one year after it was constructed, since the plasma ignition system using a flash lamp was not effective. Useful information from Leung on February 2001 that the SNS ion source succeeded in igniting the plasma by using an additional CW-13.56MHz-RF as a parallel circuit for the RF-antenna [6] solved the problem. By using additional CW-100W-30MHz-RF circuit shown by blue line in FIG 3.1.1.6, a low temperature plasma is easily ignited and maintained. The low temperature plasma is heated by the pulsed 2MHz-RF with a small RF-reflection. A block diagram of a matching circuits for 60kW-2MHz-RF is also shown in FIG 3.1.1.6.

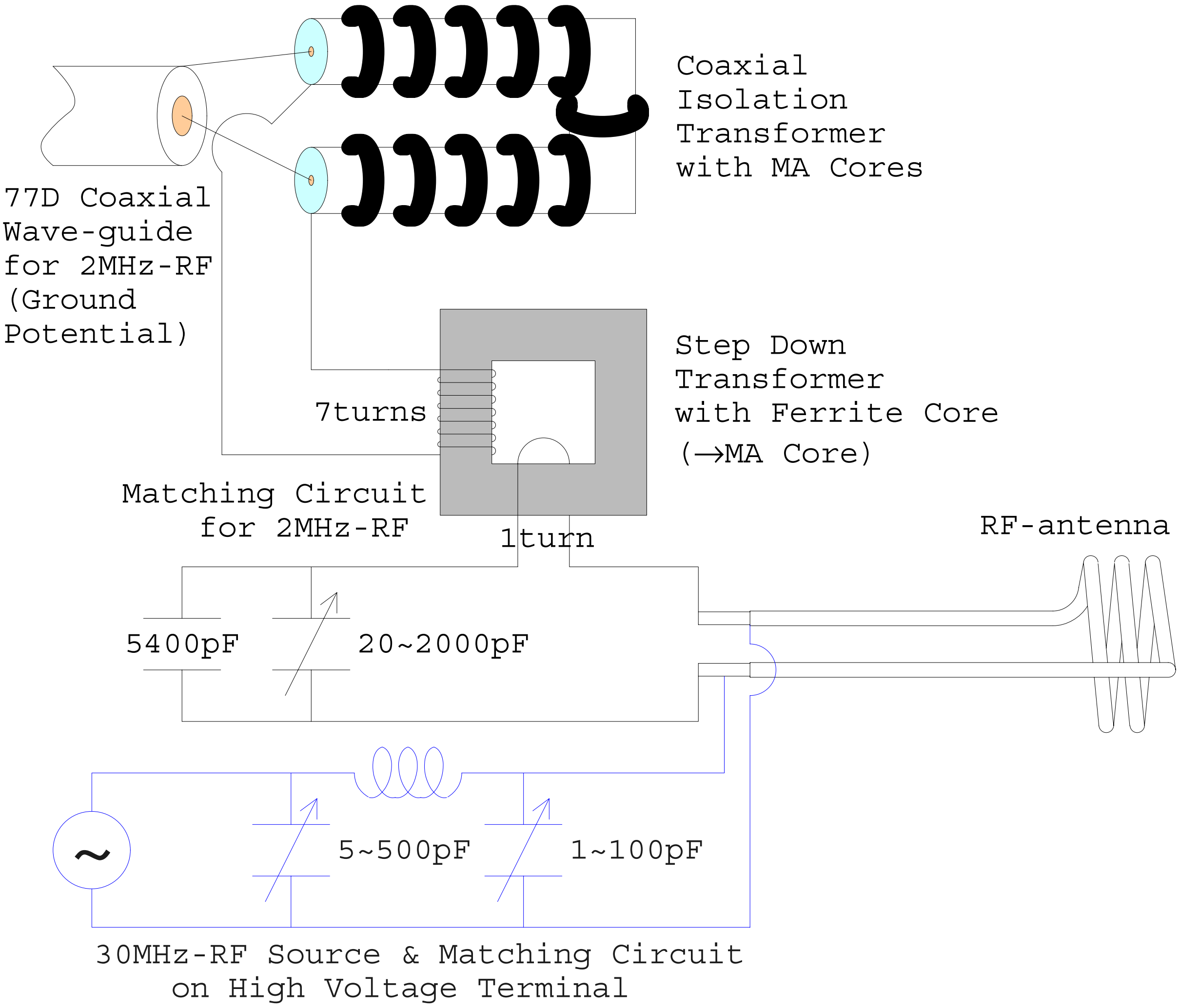

FIG 3.1.1.6 Block diagram of matching circuits for 60kW-2MHz-RF (pulse operation) and 100W-30MHz-RF (CW operation to maintain low temperature plasma).

By using the same type porcelain-coated RF-antennas used in the SNS ion source, the joint project ion source was operated at first. However, only one of the four RF-antennas had a lifetime more than several ten hours, which is removed from the arc-chamber after about a few days operation but still survives. The remaining three RF-antennas were broken less than ten hours operation. According to the suggestion of Leung, a Ti-tubing RF-antenna covered by quartz tubing is developed for the joint project ion source. The first Ti-tubing RF-antenna was examined on December 2001. Although there is no problem to input a high RF-power up to about 50 kW by using the Ti-tubing RF-antenna, the extracted H^- beam current rapidly decreased to about a quarter of an initial value with an hour operation. Since quartz vapor sputtered from quartz tubing by high temperature plasma seems to affect H^- production, the ion source operation with the second Ti-tubing RF-antenna covered by TiO_2-coated quartz tubing started early in January 2002. After two days operation, there is no remarkable decrease of the extracted H^- beam intensity is observed. A photograph of a Ti-tubing

RF-antenna covered by quartz tubing is shown in FIG 3.1.1.7. Waveforms of extracted H^- beam current and accelerated current including H^- current and electron current are shown in FIG 3.1.1.8. The extracted H^- current and electron current are 16 mA and 90 mA, respectively. Waveforms of forward RF-voltage and reflected RF-voltage measured same time with these currents are shown in FIG 3.1.1.9. The forward and reflected RF-powers measured by peak power meters were 30 kW and 0.6 kW, respectively. Since the characteristics of the 2 MHz-RF matching circuit changed rather largely by changing only the repetition rate and the temperature rise of the ferrite core was observed, the RF-characteristics fluctuation supposed to be produced by the RF-characteristics change of the ferrite core due to the temperature rise. Therefore, the ferrite core will be replaced by a metal-alloy (MA) core.

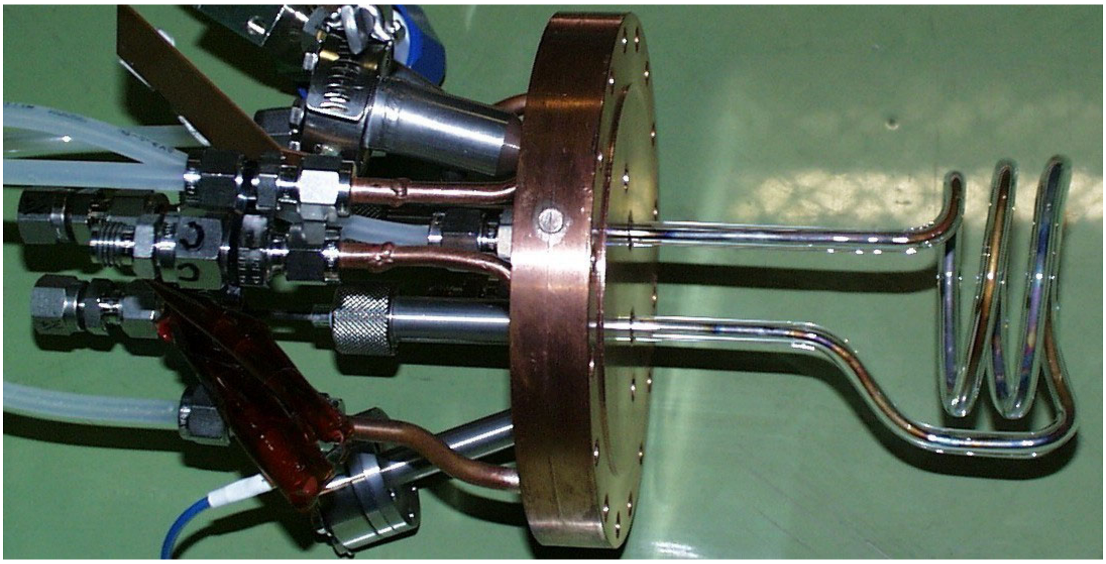

FIG 3.1.1.7 Photograph of Ti-tubing RF-antenna covered by quartz tubing installed on arc-chamber flange.

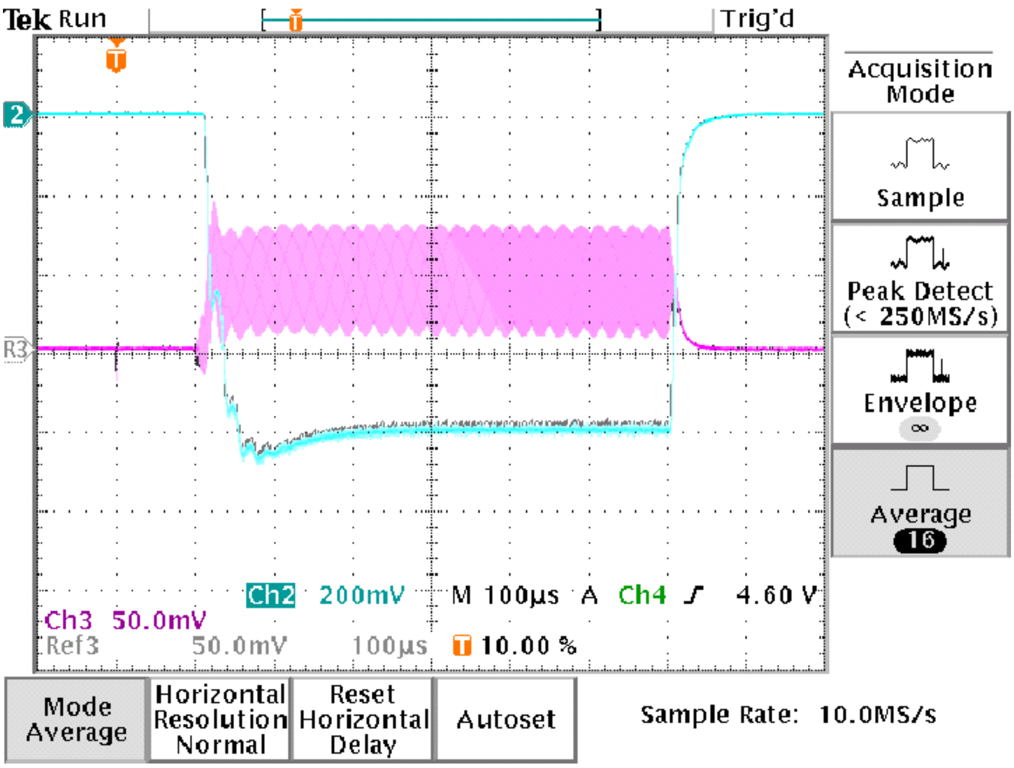

FIG 3.1.1.8 Waveforms of extracted H^- beam current (pink : 4 mA/div. ∴16 mA) and accelerated current (pink : 100 mA/div. ∴90 mA).

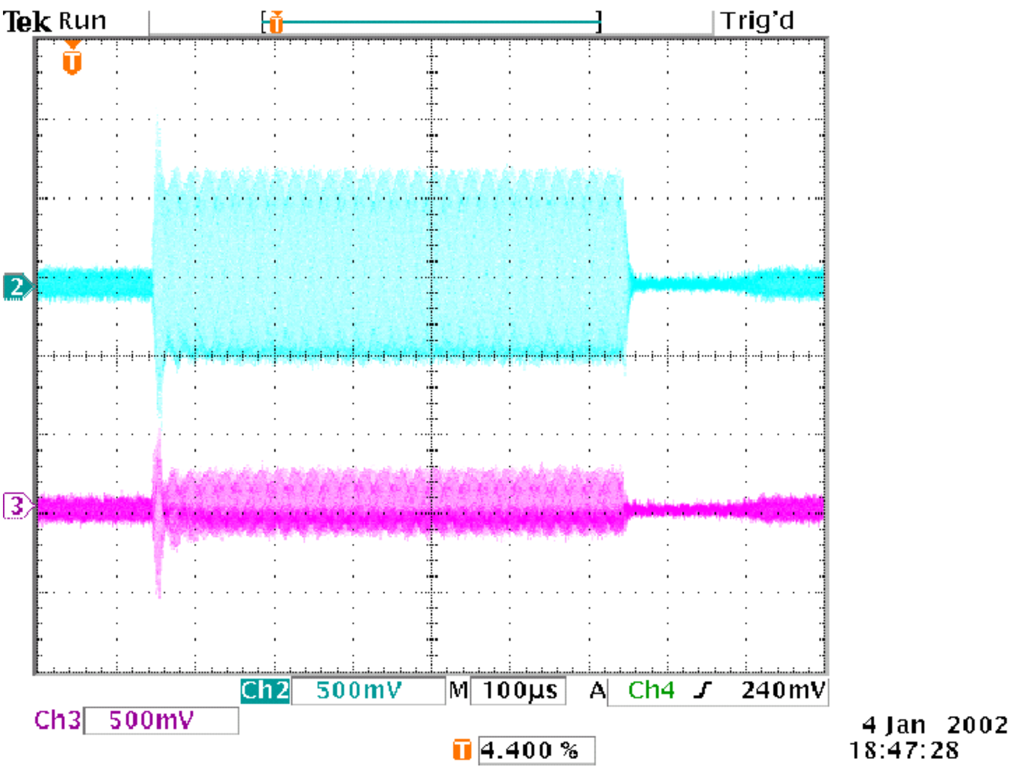

FIG 3.1.1.9 Waveforms of forward RF-voltage (blue) and reflected RF-voltage (pink).

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